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PROCESSES AND PROBLEMS IN SECONDARY STAR FORMATION

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ABSTRACT

Recent developments relating the conditions in molecular clouds to star formation triggered by a prior stellar generation are reviewed. Primary processes are those that lead to the formation of a first stellar generation. The secondary processes that produce stars in response to effects caused by existing stars are compared and evaluated in terms of the observational data presently available. We discuss the role of turbulence to produce clumpy cloud structures and introduce new work on colliding inter-cloud gas flows leading to non-linear inhomogeneous cloud structures in an initially "smooth" cloud. This clumpy morphology has important consequences for secondary formation. The triggering processes of supernovae, stellar winds, and H II regions are discussed with emphasis on the consequences for radiation driven implosion as a promising secondary star formation mechanism. Detailed two-dimensional, radiation-hydrodynamic calculations of radiation driven implosion are discussed. This mechanism is shown to be highly efficient in synchronizing the formation of new stars in $\cong 1\text{-}3 \times 10^4$ years and could account for the recent evidence for new massive star formation in several UCHII regions. It is concluded that, while no single theory adequately explains the variety of star formation observed, a uniform description of star formation is likely to involve several secondary processes. Advances in the theory of star formation will require multiple dimensional calculations of coupled processes. The important <u>non-linear</u> interactions include hydrodynamics, radiation transport, and magnetic fields.

I. INTRODUCTION

Theories that explain the formation of stars lie at the foundation of astronomy since our view of nearly all structure in the universe depends upon their existence. Progress in recent years has been possible because of instrumentation advances that have allowed observations over a wider portion of the electromagnetic spectrum. The series of steps whereby a diffuse cloud of molecular gas undergoes initial compression, eventually leading to a first generation of protostellar objects and subsequently giving rise to future generations of new stars, is slowly becoming unraveled. The past five years have brought radio wavelength observations at high resolution with the VLA, a new infrared survey by the IRAS satellite, and supercomputers which have made possible more realistic theoretical models. This article reviews recent theoretical and observational work bearing on processes that form stars as a consequence of the interactions between existing stars and the surrounding cloud material. The processes are referred to as secondary or induced star formation as opposed to spontaneous star formation. Because secondary star formation processes depend on molecular cloud morphology, we also briefly review theories for the development of the physical conditions within clouds.

We distinguish between primary and secondary star formation by following Elmegreen (1980). Spontaneous (primary) star formation follows from the gravitational collapse of part or all of a molecular cloud, and secondary star formation includes processes triggered by the first generation of stars, or by occurrences external to the cloud. Suitable triggers might include cloud collisions, supernova detonations, H II region expansions, stellar winds, or spiral density wave shocks.

New observations confirm the view that star formation is ongoing in our galaxy and the newest data suprisingly favor low mass ($\leq 5\ M_{\odot}$) objects, due to the short life and apparent rarity of O stars. It is now known that stars form deep within dense cloud cores as well as near their edges, in isolated dark globules, and perhaps within elephant trunks and cometary nebulae. The initial mass function (IMF) determined from field and cluster stars (Scalo, this volume) appears to have a certain "universal" character, although there are variations at low mass for cluster stars. At least one young cluster (NGC 2264) studied by Adams, Strom, and Strom (1983) shows no deficiency of low mass stars when compared with the field. Meusinger (1983) studied the present day mass function and found that the temporal variation of the IMF must depend upon the stellar mass. An IMF that decreases exponentially in time, over the entire mass range, fails to produce the observed present day mass function. This result is independent of the star formation rate used; therefore it makes a strong case for the continuous formation of different masses. Several different primary and secondary processes probably contribute to the star formation we observe and their relative importance is likely to depend upon the cloud structure. The complexity of molecular cloud evolution undoubtedly supports processes that depend intimately upon one another, but once initiated they appear to compete for dominance in the birth of stars. It is therefore improbable that a single, complex theory will prove comprehensive. The IMF is determined from observations of the accessible regions and it consequently represents an agglomeration of the "bones" left from all star formation and does not necessarily represent a single process (Leung, this volume).

This review concentrates on recent developments of secondary star formation processes. We emphasize processes that depend on interactions of existing stars with the surrounding cloud morphology. In section II we discuss the development of an inhomogeneous (clumped) cloud environment that appears to influence secondary star formation. We briefly discuss the roles of turbulence and cloud fragmentation, and we introduce new work on gas flow interactions. In section III we briefly review secondary star formation mechanisms including those driven by supernovae, stellar winds, and expanding H II regions. We discuss new work on a theory for the implosion of cloud clumps by radiation from O and B stars. This work introduces a new generation of numerical models based upon the solution of the equations for two-dimensional, time-dependent, radiation hydrodynamics. In section IV we consider possible directions for future research.

II. DEVELOPMENT OF THE CLOUD ENVIRONMENT

a) Does Turbulence Play a Significant Role in Star Formation?

It is becoming clear that the molecular cloud evolution leading to star formation involves interdependent processes that combine to yield an initial stellar mass function having considerable variation (Freeman 1977). The internal structure of dense clouds may strongly influence the processes of star formation that operate within the cloud. Cloud cores appear to have internal, supersonic, random motions and normally display a clumpy structure. Supersonic clumps could partake in a hierarchical cascade of energy dissipation which would affect the medium surrounding the primary generation of new stars. The stars formed in this primary generation in turn influence the next generation born within the clumpy cloud environment. The most recent observations (Sargent 1979 and Dickman, this volume) reveal that most clouds contain inhomogeneities (clumps) down to very small scales. Radio wavelength linewidths can be interpreted as due to supersonic internal motions which could easily result in density inhomogeneities. These inhomogeneities may dominate the structure of molecular clouds and set the scale for the mass spectrum of collapsing objects. Supersonic motion of density clumps in a lower density ($\cong 10^3$ cm^{-3}) cloud medium suggests turbulent flow. If turbulent flow is indeed present in molecular clouds and plays a significant role in the dynamics, the conventional picture of fragmentation requires major revision.

Considerations such as these, and observations of disordered filamentary structure in the Taurus dark cloud led Larson (1979, 1981) to study the velocity-size spectrum for a wide variety of interstellar regions that included isolated clouds, cloud complexes, and regions within giant clouds. In order to determine if motions within these regions follow a systematic flow suggestive of turbulence, he determined the three-dimensional velocity dispersion due to large and small scale variations, and thermal motions; and correlated this dispersion with region size. Larson (1981) found a relationship between the velocity dispersion σ and the region size L that can be represented by

$$\sigma(\mathrm{km\ s^{-1}}) = 1.1\ L(\mathrm{pc})^{0.38} , \qquad (1)$$

for size scales $0.1 \leq L \leq 1000$ pc. Because this power law correlation extends over several orders of magnitude and includes very small scales, he suggested that the observed motions are components in a hierarchy of interstellar turbulent motion.

More recent studies (Myers 1983, Dame et al. 1984) essentially confirmed the velocity dispersion correlation with region size found by Larson, but gave a steeper exponential dependence $\sigma \propto L^{0.5-0.6}$, and resulted in a different constant coefficient. These differences may be attributed to both the larger sample used in the current work, and to the specific determination of the dispersive velocity component. If most clouds are in virial equilibrium as Larson (1981) suggests, then the observed clumpiness of molecular clouds may result from processes other than gravitational collapse. The strong correlation between velocity dispersion and region size and the observation of irregular substructure in clouds <u>may</u> indicate the presence of turbulent flow.

Additional observational evidence supporting the presence of turbulence comes from studies of the rotational properties of molecular clouds. Fleck and Clark (1981) noted that if angular momentum transport is responsible for cloud rotation during cloud collapse, then the rotational angular velocity scales as $\omega \propto n_o^{-2/3}$, where n_o is the density required for gravitational collapse to occur. The Jeans criterion implies that low mass clouds form in regions of high n_o, and momentum conservation therefore requires that they rotate more slowly than high mass clouds. Observations indicate the opposite: small clouds rotate more rapidly than large ones. Additionally, if stars derived their angular momenta from galactic rotation, one would expect their angular momentum vectors to be aligned perpendicular to the galactic plane. Observations indicate, however, that early type stars and field Ap stars have randomly distributed rotation axes (Huang and Struve 1954; Abt, Chaffee, and Suffolk 1972). Also, the orientation of eclipsing binary orbital planes displays no evidence for a preferred galactic distribution. Taken together, these observations suggest that the rotation of clouds does not result from the ordered motion of centrifugal balance, but from a more random process; perhaps the motions are turbulent.

Myers and Benson (1983) surveyed ≅ 100 dark clouds and found significant correlations between the velocity dispersion of CO and NH_3 molecular lines and the region size, as well as between the the mean density and size. These observations extended the work of Larson (1981) into the subsonic regime for dense cloud cores and confirmed the earlier correlations found for larger clouds. Myers and Benson (1983) found the velocity dispersion $\sigma \propto L^{0.5}$ and the cloud density $n \propto L^{-1.3}$, and pointed out that the correlation between the velocity dispersion and region size is not evidence for subsonic turbulence because it can occur as a consequence of the tendency for the clouds studied to be in virial equilibrium (which gives $\sigma \propto n^{1/2}L$), and to have the nearly constant column density $N = nL \propto L^{-0.3}$. Unfortunately these correlations have equal significance, so it is unclear which of the relationships are fundamental and which are simply derivative. One cannot therefore conclude that turbulence is a fundamental process in dense cores until observations can be made with enough resolution to show significant differences in the correlations.

Some evidence for turbulent dissipation in dense cores was found in vigorous star forming regions studied by Myers (1983). He noted that the detection of dense cores in the Taurus-Auriga and Ophiuchus regions, which are known to contain many T Tauri stars, is several times the rate in Aquila which is a region with few low mass stars. Myers proposed that some cloud cores collapse rapidly and are therefore cut off from the source of turbulent energy, if this energy is supplied as in the Scalo and Pumphrey (1982) picture which attributes turbulence to collisions and drag by the clumps. Consequently, a possible conclusion is that some dense cores are on the verge of collapse because they dissipate their <u>initial</u> turbulent energy on a decay time scale $L/u \cong 5 \times 10^5$ yr which is comparable to the core free-fall time. A possible problem is apparent if one considers the presence of magnetic fields. Assuming interstellar magnetic fields to be significant in molecular cloud regions, several workers have determined the leakage of these fields through the neutrals in a medium of low fractional ionization (Mestel and Spitzer 1956, Mouschovias 1981, Shu 1983). Shu and Tereby (1984) demonstrated that, for reasonable ratios (1-10) of the initial magnetic pressure to gas pressure, the time scale for an isothermal, self-gravitating slab to lose a significant part of its initial magnetic flux is ≅ 10-10^2 sound crossing times. For the cores observed by Myers (1983) this corresponds to ≅ 10^6-10^7 yr leakage time. The time scale for collisional interactions and clump accretion to mediate turbulent energy transfer via the picture of Scalo and Pumphrey (1982) is also 10^6-10^7 yr, assuming an ≅ 1 pc cloud radius and ≅ 0.3 pc diameter clumps. The magnetic field leakage time is comparable to the turbulent energy transfer time, indicating that magnetic fields may indeed support clumps long enough for "turbulence" to affect the collapse of dense cores. It therefore appears that turbulent interactions may involve magnetic fields even down to size scales of dense cores. Shu (1984, this volume) argued that the fundamental process operating in the creation of clumps and dense cores is ambipolar diffusion, but most existing theories avoid the question of how a cloud gets its original clumpy structure and it may be that the clumps are the remains of a once turbulent magnetic eddy flow.

Additional evidence for the presence of turbulence and its importance in the star formation process may come from inspection of the low mass end of the IMF. At low masses the IMF flattens and turns over for some open clusters (Miller and Scalo 1979; Scalo, this volume). This observation led Hunter and Fleck (1982) to investigate the influence of large-scale flows in clouds on the IMF. They assumed that imposed turbulent velocity fields, which affect gravitational instability, take the form of the Gaussian distribution suggested by observations (Dickman et al. 1980). After deriving the form of the Jeans mass with such a velocity distribution, they showed that a flattening or turnover of the IMF occurs for low mass stars at the expected place in the spectrum. Moreover, they argued that the observed IMF variations for masses ≤ 1 $M_\odot$ (often taken as evidence against a universal IMF) are due to the expected variations in local turbulence within the primary clouds. Similar variations in the magnetic field strength in primary clouds could also be related to variations in turbulent structure.

Observations of the flow morphology in certain cloud systems such as the Taurus dark clouds offers compelling evidence for turbulent motion. Tajima and Leboeuf (1980) performed detailed calculations of the nonlinear Kelvin-Helmholtz instability in a compressible, supersonic flow with and without an external magnetic field parallel to the shear flow direction. These calculations used a magnetohydrodynamic particle code and the results (Fig. 1 of their paper) show the development of wavy filaments and turbulence strikingly similar to the patterns observed in molecular clouds. A possible conclusion from this calculation is that the morphology observed in clouds can indeed originate from fluid instabilities.

We conclude that the presence of some form of turbulent flow is likely present in many molecular clouds, that this motion can cause clumping and filamentary structure on many size scales, and that stars form in these regions. We will further discuss the important role of cloud inhomogeneities for secondary star formation processes in section III.

b) Fragmentation in Molecular Clouds

The existence of gas fragments within molecular clouds is no longer in doubt. While fragmentation is clearly an important aspect of star formation, we cannot overemphasize that fragmentation theory does not appear to be the only explanation for why stars form, and against which observations should be compared. Since publication of the first Protostars and Planets volume many calculations have appeared in the literature, analytic work has continued, and a few new approaches to fragmentation have appeared. Tohline (1982) presented a comprehensive review of hydrodynamic collapse including a summary of earlier pressure free calculations and comparisons of recent analytical results to three dimensional (3D) collapse calculations. The reader is encouraged to consult this review for references to individual calculations and for specific numerical detail. A subsequent (Tohline 1984) analytic approach to the collapse and fragmentation of rotating clouds clarified much of the numerical work. This work provides a new, unified framework in which to understand the variety of published numerical results.

The observational evidence in support of collapse and fragmentation primarily consists of clusters and binary and multiple systems. The clumpy nature of molecular clouds (Myers, this volume) is suggestive and is supported by observations of multiple IR sources in dense cores (Beichman, Becklin, and Wynn-Williams 1979). However, Evans (this volume) discussed the possibility that scattering from clumps may be the origin of some of the multiple IR sources.

We are in agreement with Tohline's (1982) view that with presently available computers, 3D calculations can only provide information on the first stage of the fragmention process. Physically detailed, high-resolution, 3D computations which use the present algorithms require computational capability beyond the next generation of computers. For example, the current 3D hydrodynamic models require improvement by a factor of <u>at least</u> ten in each spatial dimension. Because the time step is related to the spatial resolution, the existing methods require $\cong 10 \times 10^3$ times more computing power; but the best factor that is likely to be available with the new class VII machines is $\cong 20$. Thus, intrinsic fragmentation of molecular clouds must still be approached analytically or from an empirical, statistical viewpoint.

c) Fragment Interactions

Theoretical models for the IMF (see Scalo, this volume, and Scalo 1978 for reviews of the IMF) are based upon the premise that molecular cloud cores fragment into clumps, and that the distribution of clump masses represents the mass distribution of the stars that form. These theories calculate the asymptotic evolution of the fragment masses from an initial distribution. Processes that increase the density in a clump such as molecular line cooling, clump collisions, and accretion all act to reduce the Jeans mass thereby favoring star formation. The fragment interactions and physical conditions within the cloud are thus considered to be connected with the observed IMF. The fragmented cloud picture is supported by observations of small scale intensity variations when clouds are viewed in CO radio lines and by suprathermal linewidths interpreted as due to space velocity variations between unresolved clumps. Massive stars are not found in certain "quiescent" star forming regions (Myers and Benson 1983), and the formation process in these clouds may a primary one. Thus, in some clouds, a study of fragment interactions may adequately describe the star formation process. In other clouds, stars form from clumps as a consequence of their interaction with ionizing radiation from O and B stars. The mass distribution and presence of clumps is therefore important in secondary star formation and we find it necessary to review the most recent theoretical work on the evolution of the fragment mass distribution.

Silk and Takahashi (1979) describe the interaction between clumps by a coagulation equation for the evolution of the number density N(m,t) of clumps between mass m and m + dm from the time of their formation to time t. Coagulation models exclude explicit consideration of the clump density (size), thermodynamics, and dynamical interactions with the ambient medium. Silk and Takahashi (1979) found analytic solutions for a coagulation equation which includes the effect of accretion. Their asymptotic solution gives a deficiency in the number of clumps of low mass due to the effect of accretion on the higher mass clumps. This result means that the low mass stars observed in some clusters either originate from the field, or possibly form as a result of evaporative implosions of the higher mass clumps by hot stars.

A more detailed theory for fragment interactions was formulated by Pumphrey and Scalo (1983) in order to study the clump velocity distribution and to incorporate drag forces. Their formulation explicitly included dependence upon the parent cloud total mass, radius, and density. They wrote a kinetic equation for a clump distribution function that depends upon a clump size parameter (defined in terms of the individual fragment mass and density); and upon the fragment mass, position, and velocity vectors. Their equation is unfortunately too general to admit solutions for real systems, but they demonstrated that averaging in position and velocity space recovers the condensation-coalescence equation. The kinetic equation can be directly simulated with a numerical model which solves equations of motion for an ensemble of statistical particles. Pumphrey and Scalo (1983) contended that avoiding an explicit consideration of thermodynamic and hydrodynamic processes is an advantage because these difficult details are parameterized. Processes fundamental to clump interactions such as shocks, molecular cooling, and density compressions are incorporated only to the extent that their effects can be included in stochastic and collision terms. This is in fact a severe limitation because hydrodynamic calculations by Gilden (1984) showed that speeds for both clump collisions and drag effects are transonic and result in complicated hydrodynamic flows. For example, the conditions under which clump collisions lead to coalescence, fragmentation, or gravitational instability are more complex than assumed by Pumphrey and

Scalo (1983). Thus the additional detail provided by the kinetic equation in comparison with the coagulation theory does not seem justified. We conclude from Gilden's (1984) results, and from our own recent work discussed below, that details of the clump interactions cannot be considered as strictly external processes. A rigorous simulation must start from microscopic kinetic equations from which the hydrodynamic equations can be recovered as an approximation (Gail and Sedlmayer, 1979). It has also been demonstrated that the internal hydrodynamic evolution of clumps, e.g. their thermodynamic and dynamical condition, is fundamental to determining the time scale for star formation (Stahler 1983, Hunter 1979).

Hunter, Sandford, Whitaker, and Klein (1984) investigated the interaction of large scale ($\cong$ 1 pc) gas flows in molecular clouds. These flows may result from the action of forces external to the cloud: for example, expanding H II regions, spiral arm shocks, and supernovae detonations. Colliding gas flows form cool compressed regions. Gas flows of initial atomic hydrogen density 600 cm^{-3}, colliding at 10 km s^{-1} relative velocity initially form a disk with density $\cong 8 \times 10^4$ cm^{-3}. Stone (1970) studied colliding flows and concluded that the dense layers are dynamically unstable. Elmegreen and Elmegreen (1978) performed a linear stability analysis of gravitating layers and concluded that they fragment and form stars. Our results in Figure 1 show the velocity vectors and atomic hydrogen density contours that result from the collision of two clumpy, 5 km s^{-1} flows, each of $\cong$ 1 pc length. The collision forms a self-gravitating disk that becomes unstable, fragments, and results in the formation of a collapsing protostellar cloud and several smaller compressed regions. The fragments that form are not well represented by a distribution of discrete clumps and their evolution is therefore not properly treated by the coagulation and kinetic models. In particular, the central condensation that becomes Jeans instable grows by accretion of gas moving at sub-sonic speed between two irregular shocks. The calculations show no evidence for fragment growth or dissipation due to clump collisons. In the more general case of three-dimensional gas flows, numerous clumps of many sizes are expected to form and their evolution is likely to be determined by the velocity field that exists in gas decelerated through irregular shocks. It is thus possible that the observed CO linewidths and the clumpy structure in cloud cores result from fluid instabilities that are the consequences of the interaction of laminar gas flows. The models based on statistical interactions in a pre-existing clump population seem too simple to be useful.

To summarize, neither coagulation or kinetic clump interaction theories appear capable of completely describing the physical conditions within molecular cloud cores that lead to star formation. Bastien (1981) critically examined fragment interaction models and showed that clump collisions are important only for masses $\geq 0.8\ M_{\odot}$. Low mass stars therefore may form with the mass distribution determined by the initial fragmentation process, or else their number is determined by secondary star formation processes. A complete understanding of cloud clump morphology is beyond our present means. Until the phenomenology leading to star formation from the cloud clumps is better understood it seems to us inappropriate to pursue incomplete theoretical models that attempt to produce the "universal" IMF.

III. SECONDARY STAR FORMATION

Observations of young T-Tauri associations forming from the ρ Ophiuchus and Taurus dark cloud material support a picture in which fragmentation quiescently forms stars. Solomon (this volume) reviewed data showing that while the total number of observed, bound molecular clouds fill the available space in the galactic disk, the "strong" source ($T_A > 9$ K, $T_{kinetic} \cong 15 - 20$ K) clouds which all contain H II regions are found only in spiral arms. When the mass of all clouds is considered, the observed star formation rate ($\cong 3\ M_\odot\ yr^{-1}$) is much smaller than the rate expected ($\cong 10^3\ M_\odot\ yr^{-1}$) which infers that star formation is inhibited outside the spiral arms, and that the process is not particularly efficient. The newest data on the velocity structure within star forming clouds seems to indicate energy is input to the gas (Fleck 1983). Gravitating clouds appear to be internally supported against collapse (Goldsmith, this volume); yet stars form in their cores, and other young objects seem to have been born in low-mass, stable clumps near cloud edges.

Lada (1980) presented a body of observational evidence supporting the idea that massive stars form primarily at molecular cloud edges. It was separately suggested that their formation requires an external triggering mechanism (Lada, Blitz, and Elmegreen 1978). Several mechanisms external to the cloud can account for the compression necessary to drive star formation at either the molecular cloud surface or interior. In particular, suitable compressions result from spiral density wave shocks (Woodward, 1976), from ionization-shock fronts around sequentially formed OB subgroups (Elmegreen and Lada, 1977), from stellar winds (Castor, McCray, and Weaver 1975), from cloud-cloud collisions (Loren 1976), and from supernova explosions (Herbst and Assousa, 1978).

In this section we concentrate on theories that incorporate a triggering mechanism, emphasizing processes in which secondary star formation is either caused or accelerated by interactions between the energy output from existing stars and the cloud material. We confine most of our discussion to mechanisms that produce radiatively driven shocks because this theory is more quantitatively developed and because the other mechanisms have been included in several previous reviews. In particular, we discuss the consequence for star formation of the interaction of O and B star radiation with a clumpy cloud environment.

Massive stars are short lived and may supernova at the end of their evolution, propagating a strong shock wave in the interstellar medium which can compress clouds to instability (Woodward 1976). Herbst and Assousa (1978) compared the efficiency of density-wave and supernova shock compressions and concluded that supernovae shocks are the most important triggers; but Lada, Blitz, and Elmegreen (1978) found that the effects of expanding H II regions are much more efficient because they provide a steady source of pressure, while supernovae are impulsive sources. Only supernovae that ignite early ($< 10^6$ yr) during the evolution of an OB subgroup affect the dynamics of the star-forming layer.

Kossacki (1968) considered the graviatational instability of condensations behind a spherically converging shock and determined a criterion for the masses of the condensations. Kossacki's work predates the related study of Elmegreen and Lada (1977) who proposed that the process by which the I-S front from an OB subgroup propagates into a plane-parallel molecular cloud and creates a cool, dense, star-forming layer is a sequential one. They termed the dense layer the "cooled-post-shock" (CPS) layer. The plane-parallel CPS layer is subject to gravitational instability and it fragments to form members of a new OB star subgroup that continue the process. Sequential star formation is in superficial agreement with observations that some of the youngest OB subgroups formed near the edges of clouds, and that subgroups within an association are in temporal sequence. If one accepts the premise that external effects confine primary star formation to spiral arms, then the reason that secondary, sequential star formation fails to propagate into the inter-arm clouds must be explained. A possible explanation may be found in the work by Cox (1983) who concluded that the star formation rate during galaxy formation was much higher and that star formation in the present galaxy is inhibited.

For the Cep OB3 region, where the star formation efficiency is high and a new subgroup is forming, Sargent (1979) concluded that the onset of star formation was brought on by conditions different than the sequential star formation mechanism which now seems to operate within the association. Isobe and Sasaki (1982) studied the Orion association and reached a similar conclusion. Harvey and Gatley (1983) concluded that in NGC 6334, which contains the greatest number of protostellar OB stars of any region yet surveyed, the sequential triggering mechanism is not viable. Triggering by a spiral density wave was suggested as a plausible explanation for the widespread O and B star formation in NGC 6334. Jaffe and Fazio (1982) investigated the O and B star formation mechanism in the M 17 SW molecular cloud using the first high-resolution, high-sensitivity, far-infrared data. Their results favor triggering by a spiral shock, and they discarded the sequential star formation hypothesis because the data do not show evidence for a temporal sequence. Thus, while there is evidence that the sequential process envisioned by Elmegreen and Lada (1977) may have been very important in the pre-history of the galaxy, and that it may operate within some young associations, many secondary star formation regions seem to be the result of a different type of interaction.

The importance of star formation near H II regions has been well documented by several observational studies (see for example Blitz and Stark 1982). Blitz (1980) emphasized the effects of stellar winds from O and B stars (Castor, Abbott, and Klein 1975) as a viable mechanism for massive star formation. In this picture, winds from hot stars create ionized bubbles in the interstellar medium and compress the gas in the bubble volume into thin, dense shells. Wind driven shells are similar to the shells produced by a supernova explosion. They form a cool, dense, star-forming layer analogous to the CPS layer in the Elmegreen and Lada (1977) sequential star formation mechanism. This layer may become gravitationally unstable leading to star formation. Stellar winds may also be effective in triggering massive star formation because they stir the ambient cloud and increase the rate of clump aggregation (Silk, 1984), which in turn is proportional to the rate of star formation. Blitz (1980) pointed out that it is not obvious how one differentiates between the stellar wind star formation mechanism and the ionization-shock front mechanism proposed by Elmegreen and Lada (1977). Both expanding H II regions and strong wind outflows emanate from newly formed OB subgroups, making discrimination between these two secondary star formation mechanisms difficult. This problem was addressed by Hughes (1982) with the conclusion that an isolated B star in IC 1805 formed as a result of wind-driven shock compression.

Hydrodynamic models calculated by Sandford and Whitaker (1983) showed that a hot wind encountering a cloud fragment forms a bow shock around the denser, neutral gas. Their numerical results were confirmed by a one-dimensional, analytic analysis and hot shocks were found rather ineffective as a means to compress the clump. Cool, neutral winds were found to transfer momentum into cloud clumps supporting the Norman and Silk (1980) proposal that T-Tauri winds initiate subsequent, secondary star formation. Thus, Blitz's (1980) proposal and Hughes' (1982) conclusion that hot OB subgroup stellar winds initiate the compressions leading to massive star formation requires further study.

A major goal for observers of star forming regions must be the discrimination between the possible secondary star formation mechanisms. Improvement in the calculations of the interaction of stars with their surroundings will of course provide new observational tests. Several suggestions for observational tests have already emerged. Lada (1980) proposed looking for correlations between the spiral density wave propagation direction and the location of stellar birth complexes at the edge of giant molecular clouds. This test assumes that the giant cloud edge which first encounters the spiral wave will be the edge where stars form first. This is not neccessarily the case. If the cloud structure is sufficiently smooth near the edge, star formation may be more efficient in the clumpy interior. A more promising test would be a correlation between the temporal sequence of young subgroups and the direction of galactic rotation inside the co-rotation radius (Lada 1980).

The importance of supernovae as a triggering mechanism would benefit by the discovery of massive star formation within a supernova remnant. The prospect of an observation that does not show an ionization-shock front due to the O star trigger is small (Elmegreen 1980) because such ionizing radiation always preceeds the explosion. The CMa R1 region cited by Herbst and Assousa (1977) as evidence of supernova triggered star formation has an ionization front in the vicinity of the expected compression direction. Thus, without additional evidence for the origin of this front, one does not know if it results from the supernova or from the original O star. An interesting case where secondary star formation could potentially result from several mechanisms is currently being studied by Ho (private communication, 1984). Ho observed a compact H II region (G34.1) that is $\cong$ 40 pc projected distance from W44, which contains a supernova remnant. The H II region is cometary in appearance, surrounds a dense neutral globule, and the ionization appears to point precisely to the location of the remnant center. Ho estimates the amount of energy necessary to deform the neutral globule is $\cong 10^{50}$ ergs (close to the energy of the supernova explosion). The remnant and shock have not yet reached the compact H II region so the direct action of the supernova is not responsible for the ionization in G34.1. Another possibility is that the H II region is a result of prompt X-ray radiation from the supernova. Calculations of this effect (Klein and Chevalier 1978) show that during the interval of peak X-ray luminosity ($\cong 10^3$ s) only $\cong 10^{48}$ ergs is generated. The 40 pc distance would dilute and absorb the ionizing flux of the original O star, excluding this as a possible source. The most probable remaining possibility is that the H II region results from the stellar wind of the original O star. Ho and collaborators are continuing to study this very interesting region.

Calculations that follow the evolution of an ionization-shock front in a molecular cloud at the time a supernova precursor explodes and augments the clump compression are badly needed. These calculations could help to clarify the relative importance of each process while providing signatures of their combined effects. In the following subsections we discuss recent work that investigates the consequences of ionization-shock fronts generated by O and B star radiation that propagates into an inhomogeneous cloud environment. These calculations provide the background for future more complex calculations involving additional impulsive forces from stellar winds and supernovae.

a) Radiation Driven Implosions

Massive stars are such strong sources of energetic radiation that they have an important, immediate influence on their local environment (Smith 1982). Their radiative output generates enormous H II regions in low density gas, they create compact H II regions in dense cloud cores, and they can evaporate existing cloud clumps (Whitworth 1979). Klein, Sandford and Whitaker (1980, hereafter KSW1) showed that hot stars drive convergent ionization-shock (I-S) fronts into cloud clumps, imploding them to gravitationally unstable densities. This extended the previous work by Oort (1954) and Dibai (1958, 1960). LaRosa (1983) examined a simplified radiative implosion model and analytically derived estimates of the conditions for clump implosion or erosion by radiation.

In a series of papers investigating the effects of I-S fronts in a clumpy cloud, Klein, Sandford, and Whitaker (1980, KSW1; 1983, hereafter KSW2), and Sandford, Whitaker, and Klein (1982a,b, hereafter SWK1 and SWK2; 1984, hereafter SWK3) presented results of calculations with a new 2D, two-phase flow, radiation hydrodynamics code. We used an implicit, multiphase hydrodynamics method (Harlow and Amsden 1975) which is coupled to a 2D, time-dependent, discrete-ordinate technique for radiative transfer due to Lathrop and Brinkley (1973). Thus, for the first time, the frequency and angle dependence of the multi-dimensional equations of transfer and gas dynamics were considered. Our cylindrically-symmetric, Eulerian-mesh radiation hydrodynamics method included a second material phase (dust) moving relative to the compressible gas which consisted of hydrogen ions, neutrals, and electrons. We solved the set of hydrodynamic conservation equations for the gas and dust phases simultaneously with a combined equation of transfer that includes three frequency groups for ionizing radiation absorbed by gas and attenuated by dust extinction; and with the appropriate ionization rate and constitutive equations. The dust and gas fluid components are connected through phase changes, if they occur, and by appropriate heat and momentum interchange functions.

b) Implosions by Single Stars

The results of KSW1 showed that ionizing stellar radiation which irradiates only one face of a cloud clump can effectively compress the clump with the shock which precedes the ionization (I-) front. In SWK1 the adiabatic results of KSW1 were extended by including a molecular cooling model. Results were compared for the implosion evolution of a low ($\cong 1 \times 10^{-5}$ $M_\odot$) mass globule and one of higher ($\cong 2$ $M_\odot$) mass. The physical environment modeled by our calculations treated the effect of ionizing blackbody radiation from an O9 star ($T_* = 30000$ K) approximately 8 pc distant from a molecular cloud clump.

Two cases from SWK1 which indicate the important results of the radiative implosion model will be summarized. Both calculations were performed on a 25 × 50 zone Eulerian mesh, and the diluted non-grey O star radiation was incident on a clump having initial atomic hydrogen density $n_H \cong 600$ cm^{-3}. The neutral clump and surrounding ionized gas were initially in approximate pressure equilibrium. The temperature in the neutral clump was $T_g \cong 15$ K, and the surrounding ionized medium had an electron density $n_e \cong 0.24$ cm^{-3} and $T_g \cong 15000$ K. The low mass case had a grid size of $\Delta r = \Delta z = 1 \times 10^{15}$ cm, and the higher mass case had a grid size 50 times larger. In the low mass case the computing cells were optically thin and the I-front was resolved, covering about two mesh cells, but the ionization structure was not resolved in the higher mass case. In neither calculation was the shock resolved. The simple scheme used for molecular cooling gave isothermal shocks near 100 K.

In each case the radiation flowed around the curved clump face generating an I-S front which surrounded most of it, and in which motions were focused toward the symmetry axis. The interaction of the radiation with the neutral clump also caused hot ionized gas to expand outward into the intercloud medium. The I-S front progressed into the clump and soon, a convergent shock separated from the I-front and traveled into the interior of the clump. By 1300 yr, for the low mass case, the convergent shock drove neutral gas toward a point on the symmetry axis and produced a centrally condensed globule with a compression ratio ≅ 70. Woodward (1976) found similar motions toward the symmetry axis, resulting from a shockwave striking a clump. Figure 2 presents, for the low mass case, contours of H I number density and H II number density at t ≅ 1300 yr. The contours are superimposed on the hydrogen gas velocity vectors at the same time. The separation of the shocked neutral material from the ionization front is evident as well as the higher ionization of the cloud material facing the distant O9 star. It is seen that the flow of radiation around the original clump surface was effective in driving the convergent shockwave that produced a large compression in the neutral globule. The convergent flow in the clump and the outward flow in the H II region are well illustrated by the velocity vectors.

For the higher mass case, the evolution proceeds in a similar fashion and at the end of the calculation (≅ 6 X 10^4 yr) a toroidal globule formed near the symmetry axis. At this time the compression ratio is nearly 19 and the mass in the toroidal condensation is ≅ 0.8 $M_\odot$. In both models, about 40% of the initial cloud gas is compressed into the globule, with the remaining mass ablated back into the intercloud medium.

While neither globule was Jeans unstable at the end of the calculation, the process of radiation driven implosion was effective in producing small dense structures. Two important considerations are worthy of comment. First, the simple molecular cooling law used gave minimum temperatures of about 100 K. Cooling by CO molecules would reduce the minimum temperature to much lower values, yielding cooler, denser structures of smaller Jeans mass. Second, Hunter (1979) analysed the effect of an inwardly directed velocity flow on the Jeans mass and found (for velocities of 1 km s^{-1} at 10 K) reductions of the Jeans mass by factors of 5-20. These effects augment the radiation driven implosion, and the process may be sufficient to drive even small globules to Jeans instability providing they are not evaporated by the ionizing radiation from the star.

Some recent observations tend to support the radiative implosion model. Felli, Johnston, and Churchwell (1980) found a point source near an arclike ridge of ionization in radio continuum observations of M 17, and they concluded that the object may be an example of star formation induced by shock focusing. More recently, McCutcheon, Roger and Dickman (1982) reported on CO observations in the vicinity of IC 5146 in which they found three regions of enhanced emission, all on the edge of the Sharpless region S125. They discussed the need for a source to maintain the emission and concluded that an embedded protostar (about B1) is a likely candidate for the most intense region. They also proposed that <u>all three regions</u> were formed by an interaction with the H II region generated by the central star of S125. The three compressed regions could have formed as a result of radiative implosions driven by the central star. Reipurth (1983) observed bright rimmed globules in the Gum nebula and concluded that some are forming stars as a consequence of compression by converging I-S fronts.

c) <u>Implosions by Multiple Sources</u>

Our first calculations (KSW1 1980, and SWK1 1982) investigated the mechanism of radiation driven implosion by single O stars and resulted in highly compressed globules nearly massive enough to gravitationally collapse to form new stars. These results led us to the conclusion that radiation driven implosion is a promising star formation mechanism and that the morphological structure surrounding a young cluster of O stars may significantly influence the subsequent star formation in the cloud interior.

The mass spectrum of young stellar objects would depend upon the size scale of the initial inhomogeneities.

Radio observations of ultracompact H II (UCHII) regions by Ho and Haschick (1981) and Dreher et. al. (1983) discovered multiple sources having size scales comparable to their separation distances (≤ 0.1 pc), and formation time scale differences less than a few tens of thousands of years. These small scale structures were interpreted as the result of the most recent episode of star formation which produced new members of an OB star cluster. Further radio continuum and line observations by Haschick and Ho (1983) of O and B star formation in the W33 complex show that the most recent episode of star formation resulted in massive stars confined to a 1 pc core within the dense molecular gas. The appearance of a highly clumped H II region and evidence for several sites of star formation suggests cluster formation within the core of W33. These observations challenge the more traditional view that massive star formation is confined to the surface of molecular clouds (Lada, 1980) and demonstrate that they may form throughout the interiors of cloud complexes as well. Optical observations are largely responsible for the suggestion that the birthplace of O stars is at the surface of molecular clouds. This could be a selection effect because optical identification of O stars is normally restricted to cloud surfaces due to interior obscuration. In addition, observations based on giant H II regions could reflect the disruption of cloud material by O stars born in their interior. These stars would now have the appearance of being born on the cloud edges. This opens the possibility for new secondary star formation mechanisms that operate in cloud interiors and depend on the cloud morphology for their efficiency.

Motivated by these observations, and by the compelling evidence that widespread clumping and inhomogeneities exist in molecular clouds down to scales ≤ 0.1 pc throughout star forming regions, we calculated (KSW2 1983) the detailed time-dependent evolution of an inhomgeneity initially containing 84 $M_\odot$ that is embedded between and irradiated by two O7 stars, each at a distance of 0.5 pc from the clump. The inhomogeneity was represented by a sphere of neutral hydrogen at a temperature T = 30 K and with uniform density n_H = 3000 cm^{-3}, and was surrounded by an intercloud medium that was fully ionized with density n_H = 0.24 cm^{-3}. The objective of the calculation was to follow the evolution of a radiatively compressed inhomogeneity embedded in the environment produced by an earlier generation of O and B stars, and to determine the consequences of this evolution for new star formation. Our calculations were performed with the 2-D, implicit, Eulerian, radiation-hydrodynamics code described previously (SWK1) and did not include the effects of dust and self-gravity. The embedded inhomogeneity was placed on the cylindrical symmetry axis colinear with the ionizing O stars.

The results showed that within 10^3 yr the ionizing UV radiation ablates a layer of plasma which flows from the surface of the neutral clump, resulting in the propagation of two-dimensional shockwaves moving into the neutral gas. The time evolution of this clump is illustrated in Figure 3 at 1×10^4, 1.5×10^4, and 2.0×10^4 yr. Convergent, strong shockwaves propagate within the clump and produce density enhancements (compressions) of 4.4, 7.6, and 24.0 over the ambient density at the three respective times. Dynamical evolution suggests that individual local sites of high density, initially present at low density due to the "staircase" effect of discrete zoning, are amplified by the shock convergence. At 2×10^4 yr the converging shocks coalesce and drive the individual enhancements into a disk. The possibility exists that local density or pressure fluctuations could amplify during the compression and later fragment to become individual compact objects. At 3×10^4 yr the convergent shocks surrounding the clump interact nonlinearly in the interior producing a compression factor of 170 over the initial density. The final density is $n_H \cong 5 \times 10^5$ cm^{-3}. The globule that forms has a radius < 0.1 pc, $T_g \cong 200$ K, and an ablation outflow speed > 30 km s^{-1}. The calculation was terminated because the grid lacks sufficient resolution at the longest times. Of the initial 84 $M_\odot$, 40 $M_\odot$ remained intact and 44 $M_\odot$ evaporated from the object into the interclump medium. The compressed globule was found to be a factor of 3 smaller than the static Jeans mass at 3×10^4 yr, but cooling due to molecular species other than H_2 could drive the clump temperature to T_g < 100 K and would cause gravitational collapse in a free-fall time < 6×10^4 yr. An estimate of the mass lost due to the continued irradiation of the imploded clump was made by KSW2 (1983). Their estimate was made by combining mass conservation with analytic expressions due to Kahn (1969) relating the Lyman continuum flux at the clump to the particle density and temperature, and to the flow velocity in the ablated, ionized gas. By equating the derived mass loss over a given time interval with the mass inside a shell of given radius and thickness, KSW2 (1983) obtained an estimate for the evaporative lifetime of the compressed clump. For an illuminating star that is O7 or earlier the lifetime is $\cong 3 \times 10^5$ yr, but for an O9 or later star the lifetime is $\cong$ 1-2 $\times 10^6$ yr. The inclusion of dust effects (see subsection d) would increase the lifetime. Hence, if the object is gravitationally unstable at the time of maximum compression by the convergent shocks, it would likely collapse in $\cong 10^4$ yr.

The 2D symmetry of these calculations leads to the formation of a disk and later to a toroidal structure, either of which may fragment before gravitational collapse. In a real object, the radiation driven implosion would occur in three-dimensional geometry. Some indication of the stability of the toroid resulting from 2D calculations may be obtained by considering the effects of non-axisymmetric perturbations on a rotating, self-gravitating torroidal object. Cook (1977) considered this question by performing time dependent, 3D, hydrodynamic calculations of collapsing, adiabatic torroids. The Virial theorem relates the gravitational, internal, and rotational energies of an object in equilibrium; and, when combined with an approximate criterion for the torroidal fragmentation, it yields a stability condition. Using Cook's (1977) 3D results for the torroid resulting from our (KSW2, 1983) calculation we find that it would fragment into $\cong$ 2 masses if rotating at 2×10^{-14} s^{-1}. As the temperature of the torroid drops the thermal pressure which resists the action of a perturbation is reduced, and the theory predicts fragmentation into more objects. Fragmentation might produce several objects, each of 6 - 7 $M_{\odot}$, and could therefore lead to low mass star formation. Alternatively, inhomogeneities with initial masses > 84 $M_{\odot}$ driven to high compression by shock focusing could result in massive star formation even for unstable torroids. On the other hand, an initial core-halo density distribution might keep the collapse on the axis leading to larger mass compressed clumps. In three dimensions, irradiation from several surrounding stars might surpress torroidal growth and could lead directly to rapid massive star formation.

The key point made by KSW2 (1983) is that <u>shock</u> <u>focusing</u>, which occurs in either 2- or 3D geometry, is a consequence of radiation driven implosion that substantially increases the compression and is expected to drive clumps to gravitational instability on time scales short compared to evaporation times. This provides a mechanism for forming additional stars within an OB subgroup that is born in a molecular cloud core. Because the multiply driven implosion mechanism is efficient (40-50% of the clump mass remains after evaporation), it is possible for a few O and B star triggers to implode many embedded clumps to form a new generation of stars in a few times 10^4 yr (Figure 4). If this process gives birth to O stars, the additional imploded clumps could form yet another generation of stars. Thus a region 1 pc in size could contain several newly formed O and B stars and UCHII regions that appear to be coeval within a few tens of thousands of years. The densities and time scales found in our calculations agree well with the observations of Ho and Haschick (1981) lending support to multiply driven radiation implosions as the mechanism for synchronizing the formation of OB subgroup stars.

An alternative explanation for the observations was offered by Shu (1983, private communication). If the individual stars have peculiar velocities on the order of the sound speed, their successive Stromgren spheres are left behind to recombine in one crossing time. Hence the star never stays long enough in any one place to build up a large H II region, and can be older than the apparent age. These alternative theories can be tested by a high sensitivity continuum study of the low-level emission in UCHII regions, looking for the interaction between H II regions and surrounding neutral material or evidence of low level emission trailing the condensations.

Clearly, more theoretical work remains to explore the consequences of multiply driven radiation implosions. As mentioned above, it is important to determine the efficiency of the implosion mechanism for O star triggers that are also blowing stellar winds, or for stars that enter a supernova phase while contributing large amounts of ionizing radiation to imploding embedded inhomogeneities. It also remains to be shown how structure within clumps affects the convergent shock and to determine if the masses that can be compressed will survive evaporation to form low mass stars.

d) Effects of Dust

When dust is included as a component of the interclump medium, radiation pressure from distant O stars accelerates grains with respect to the gas and the I-S front becomes dust-bounded as it converges into a clump (SWK3). The I-front speed slows to that of the dust grains which undergo drag interactions with the gas ($\approx$ 2 km s^{-1}). The time scale to reach the same compression is longer than in the absence of dust, but it remains short compared with the free-fall time. For I-front densities $\cong$ 200 cm^{-3} and with dilute radiation fields, sputtering and vaporization effects are not important. Grains survive and accumulate in the I-front and the dust-to-gas mass ratio increases from 0.02 to 0.04-0.13. Gravity becomes an effective collapse force at about the time the I-front becomes dust-bounded and its effect on the subsequent dust and gas distribution remains to be determined. The evolution of a globule in these circumstances is shown schematically in Figure 5. The lifetimes of cloud clumps are found to be longer than estimated by LaRosa (1983) because globules become centrally condensed and are less easily eroded. Dust in the I-front attenuates ionizing radiation and reduces the ablation rate, and incident radiation is also absorbed by the evaporated (ablated) gas to maintain its ionization. Low mass ($< 1\ M_{\odot}$) globules can be confined by a dilute radiation field long enough to become gravitationally unstable. It is thus proposed that isolated, stable dark globules were formed by radiative implosions of small cloud fragments at the distant edges of an ancient H II region.

When effects of dust are included, low mass globules are stable long enough to contract and to form a star if they are in the presence of a weak, external, ionizing radiation field. Observational evidence for star formation in dark globules is increasing. Krugel et al. (1983) and Keene et al. (1983) independently concluded that the Bok globule B335 is forming, or has recently formed, a star of ≅ 1-2 $M_\odot$. Jones et al. (1980) and Jones, Hyland, and Bailey (1984) made extensive observations of Bok globule 2 in the Southern Coalsack. This ≅ 12 $M_\odot$ object shows no evidence for a central density enhancement, as would be expected for a gravitationally contracting globule. The stability of the globule is interpreted as being due to some form (turbulent or magnetic) of internal support. Our calculations (SWK3) indicated that at an early stage in the evolution of a globule confined by an I-S front, the density profile becomes flat and the internal motions are acoustic. Additional calculations are needed to determine the effect of the demise of the radiation source, leading to the collapse of the I-S front. It is possible that reasonably uniform, stable globules containing sonic (turbulent?) gas dynamical flows could form. A theoretical prediction of the probable lifetime and eventual fate of such globules would be of great observational interest.

Globules compressed by radiation driven implosions are predicted to contain relatively more dust than ones that gravitated from cloud fragments, and second generation protostellar objects would therefore be born with far-infrared signatures different than those from objects formed by a different mechanism. For NGC 2264 which contains hot stars capable of imploding clumps, Adams, Strom, and Strom (1983) concluded the star formation history extends over ≅ 10^7 yr, and that the youngest, low-mass, pre-main sequence stars show circumstellar dust emission. Wesselius, Beintema, and Olnon (1984) studied young objects in the Chameleon I dark cloud (which contains no O and B stars) and found two pre-main sequence A0 stars embedded in large, extended (≅ 0.2 pc) dust complexes. These observations, and those of Baud et al. (1984) showing that G and K-type young stellar objects have relatively little dust, are consistent with the conjecture that primary star formation from cloud fragments forms extended dust cocoons but secondary formation in imploded globules results in compact, circumstellar emission.

The stellar material originating from the central condensation of an imploded globule contains the ambient cloud abundances; but the envelope, atmosphere, and accretion disk or shell forms from dustier gas and is therefore predicted to be metal-rich. Main sequence stars showing evidence for a far-infrared excess, such as Vega (Aumann et al. 1984), could therefore represent a population formed by radiation driven implosions and their statistical frequency of occurrence would measure the efficiency of the process. The formation of low mass, isolated, main sequence stars would be relatively rare if the process is 1-2% efficient (Reipurth 1983). Dark globules may provide the best examples of isolated, quiescent star formation. New observations to determine the conditions in a large number of globules are needed. The evolutionary history of dark globules could perhaps be determined if their internal structures are found to form a progression, and if the relationship between the isolated globules and those embedded in H II regions can be established.

e) Importance of Radiation Driven Implosions

The efficiency of radiation driven implosions for stars forming from cometary nebulae in the Gum nebula was estimated to be ≅ 1-2% (Reipurth, 1983). The star formation efficiency required to produce a bound cluster is high (> 50 %) according to Wilking and Lada (1983), but the overall formation efficiency for field stars is apparently quite low (≅ 0.1%). Because hot stars tend to disrupt their parent clouds, and in the process implode some of the fragments; one expects that this secondary star formation may be more efficient than the overall process, but perhaps less efficient than required to form bound clusters. Near the edges of an expanding H II region, radiative implosions of individual clumps may tend to form lower mass objects because the compressions from single sources are weaker than within an OB subgroup, time scales are short compared to the lifetime of the source star, and perhaps because the clumps driven to instability are small ones that could not otherwise contract. O and B-type stars are observed to be forming in dense cloud cores and our calculations show that radiative implosions in these regions may lead to an higher efficiency of massive star formation on a short time scale. Thus we believe that radiatively driven implosions may stimulate star formation over a wide mass range, in different cloud morphologies, and with correspondingly different formation efficiencies. Observers are encouraged to test this view.

As an example of a the possible importance of secondary star formation, possibly driven by radiative implosions or stellar winds, we review observations of the NGC 2264 region. Adams, Strom, and Strom (1983) employed new, unsharp-masking methods to locate and include faint, low mass stars in this star forming region. No evidence for a deficiency in the low mass IMF was found. On the other hand Scalo (1978) and Scalo (this volume) presented evidence for a real deficiency in the numbers of low mass stars for a variety of galactic clusters, and he concluded (in agreement with coagulation theory results) that the low mass stars found in some clusters may form via a different mechanism. This mechanism may be radiation driven implosion. NGC 2264 appears to be an excellent region in which to study the star formation process at low mass.

A generally accepted suggestion that the star formation rate is mass dependent followed Herbig's (1962) study of NGC 2264, and is based upon the difference between nuclear ages of clusters and the (greater) ages of low mass members. The conclusion is drawn that low mass stars form first, but this result is not explained by coagulation models (primary star formation) or by radiative implosions (secondary star formation). Ages for low mass, pre-main sequence stars are determined by comparing their positions in the HR diagram with theoretical isochrones. Based on the older, widely used isochrones Adams, Strom, and Strom (1983) concluded, in agreement with Herbig's (1982) result, that the star formation rate in NGC 2264 peaked at different times in the past; and that the lowest masses began to form first. Stahler, Shu, and Taam (1980a,b; 1981) presented a new, efficient, more general approach to pre-main sequence evolution modeling and calculated evolutionary tracks that differ from the old results. Stahler (1983) examined the age determination problem in view of the new calculations and identified a "birthline" in the HR diagram for T-Tauri stars. The new stellar birthline is in good agreement with a large number of observations for several clusters and necessitates a revison of the ages inferred for low mass stars. Corrected ages result in star formation rates that increase from the past to the present for all masses, and the rate peaks found by Adams, Strom, and Strom (1983) are thus removed. The increasing star formation rate may be due to secondary star formation processes, such as radiation driven implosion.

New far-IR observations of $C^{18}O$ sources within condensations in some cloud cores just beginning to form stars reveal the youngest objects to be B stars (Jaffe et al. 1984). A similar result, but for O stars, is found in new, high resolution radio continuum observations of cloud cores with the VLA (Ho, private communication 1984). Observations of star formation in cloud cores now favor the possibility that hot stars form at the earliest times. Because implosions driven by ionizing radiation can occur only after hot stars form, the numerous low mass objects found by Adams, Strom, and

Strom (1983) would necessarily be of recent origin. One reason that low mass stars may be younger than is inferred from theoretical isochrones is the reduction in the contraction time scale due to dynamical (ram) effects of the implosion process (Stahler 1983, and Hunter 1979).

Finally, observational advances bring closer the possibility that low mass star formation may be directly observed. Small scale clumping exists in the molecular gas surrounding the compact H II region W 3(OH), and the clump sizes ($\approx 2.5 \times 10^{16}$ cm) and densities ($n_{H_2} \approx 10^6$ cm^{-3}) were determined by Dickel et al. (1983). The clumps represent fragments in a dense molecular shell and each contains 2-5 $M_\odot$. These can be interpreted as resulting from radiation driven implosions of density inhomogeneities in the cloud that surrounds the central star. Secondary star formation may thus be observed to accompany the birth of a hot star if the surrounding cloud is sufficiently inhomogeneous.

V. DIRECTIONS FOR FUTURE RESEARCH

In this section we discuss some of the observational and theoretical research necessary for further understanding the secondary star formation process. For theoretical prospects, we view as essential the continuation and improvement of multi-dimensional numerical models. These provide the most detailed, fully non-linear predictions of the observable signatures of secondary star formation. New, more detailed multidimensional calculations are crucially needed. In particular, it will be important to delineate the differences in the interaction with clumpy molecular clouds of H II regions, stellar winds, and supernovae; and to quantify the relative efficiency of each. Our work strongly suggests that two-dimensional, radiation-hydrodynamics must include a variety of physical detail in order to understand the fundamental interaction of radiation driven shocks in inhomogeneous clouds. A theoretical understanding of molecular cloud morphology is as important as is numerical modeling.

The radiation driven implosion model must be further studied with improved constitutive relations including the effects of additional molecular coolants, dust grains, and self-gravity. It is of particular importance to determine to what extent the masses of stars that can form depends on the degree of inhomogeneity and clumpiness in a molecular cloud. It will be important to combine the results of dynamical radiation implosion models with a code that calculates radio-line spectra. This will require the development of a new, 2D, moving-atmosphere, line-transport code. The resulting line spectra will provide the characteristic signatures for the different models.

The hydrodynamic interaction of colliding clouds requires further theoretical study in order to interpret observations of cloud cores. The process by which gas flows can lead to cloud inhomogeneities and to transonic, random motions can be understood by significantly increasing the resolution of observations made at the CO wavelengths. An analysis to determine the infrared signatures of cloud fragments would be useful to study the effects of gas-dust interactions.

The immediate future of star formation theory lies in the interpretation of newly acquired data. A complete far-IR survey is needed to determine the extent of massive star formation within cloud interiors. Radio continuum studies with high dynamic range are needed of small scale structures within UCHII regions. These regions are potential sites of star formation due to radiation driven implosions. Observations of continuum radiation surrounding these structures should provide important clues as to the relationship between new stars, their cloud environment, and the primary triggers. High sensitivity studies of molecular lines in new secondary star forming regions are needed to obtain detailed velocity maps. These are necessary to study the ionized gas ablated from cloud inhomogeneities as well as to define the velocity structure in shocked regions. Observations of shocked regions may enable us to distinguish between the various triggers responsible for secondary star formation.

Our understanding of secondary star formation will advance most rapidly if we can successfully combine new, numerical models with observations. Large-scale numerical calculations, similar to those described in this chapter, intelligently guided by analytic work, will play an increasingly essential role. New supercomputers, such as the Cray-XMP series and machines being designed in Japan, will stimulate the development of new numerical methods and will make possible calculations more amenable to observational interpretations. There can be little doubt that numerical calculations will continue to play an important role in astronomy, and it is possible that the next decade may bring forth a comprehensive theory for the formation of stars.

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REFERENCES

Abt, H. A., Chaffee, F. H., and Suffolk, G. 1972. Rotational Velocities of Ap Stars. Ap. J. 175:779.-785

Adams, M. T., Strom, K. M., and Strom, S. E. 1983. The Star-Forming History of the Young Cluster NGC 2264. Ap. J. (Suppl. Ser.) 53:893-935.

Aumann, H. H., Gillett, F. C., Beichman, C. A., deJong, T., Houck, J. R., Low, F., Neugebauer, G., Walker, R. G., and Wesselius, P. 1984. Discovery of a Shell Around Alpha Lyrae. Ap. J. (Letters) 278:L23-L27.

Bastien, P. 1981. Fragmentation, Fragment Interactions, and the Stellar Mass Spectrum. 1981. Astr. Ap. 93:160-162.

Baud, B., Young, E., Beichman, C. A., Beintema, D. A., Emerson, J. P., Habing, H., Harris, S., Jennings, R. E., Masden, P. L., and Wesselius, P. 1984. High Sensitivity IRAS Observations of the Chamaeleon I Dark Cloud. Ap. J. (Letters) 278:L53-L55.

Beichman, C. A., Becklin, E. E., and Wynn-Williams, C. G. 1979. New Multiple Systems in Molecular Clouds. Ap. J. (Letters) 232:L47-L51.

Blitz, L. 1980. Star Forming Molecular Clouds Towards the Galactic Anticentre. In Giant Molecular Clouds in the Galaxy, eds. P. M. Solomon and M. G. Edmunds (Oxford:Pergamon Press), pp. 211-229.

Blitz, L. and Stark, A. A. 1982. A CO Survey of 372 Optical H II Regions. In Regions of Recent Star Formation, eds. R. S. Roger and P. E. Dewdney (Boston:D. Reidel), pp. 209-212.

Castor, J. I., Abbott, D. C., and Klein, R. I. 1975. Radiation-Driven Winds in Of Stars. Ap. J. 195:157-174.

Castor, J. I., McCray, R., and Weaver, R. 1975. Interstellar Bubbles. Ap. J. (Letters) 200:L107-L110.

Cook, T. L. 1977. Three-Dimensional Dynamics of Protostellar Evolution. Ph.D. thesis, Rice Univ. (report LA-6841T, June 1977, Los Alamos National Laboratory).

Cox, D. P. 1983. Self-Regulating Star Formation: The Rate Limit Set by Ionizing Photons. Ap. J. (Letters) 265:L61-L62.

Dame, T., Elmegreen, B., Cohen, R., and Thaddeus, P. 1984. untitled, in preparation.

Dibai, E. A. 1958. Evolution of Globules in the Vicinity of Hot Stars. Sov. A. J. 3:429-432.

___________. 1960. The Origin of Cometary Nebulae. Sov. A. J. 4:13-18.

Dickel, H. R., Lubenow, A. F., Goss, W. M., and Rots, A. H. 1983. VLA Observations of H_2CO in W 3(OH). Astr. Ap., submitted.

Dickman, R. L., Kutner, M. L., Pasachoff, J. M., and Tucker, K. D. 1980. Turbulence in the Dust Cloud L134: High-Resolution Observations of 6 Centimeter Formaldehyde Absorption. Ap. J. 238:853-859.

Dreher, J. W., Johnston, K. J., Welsh, W. J., and Walker, R. C. 1983. Ultracompact Structure in the HII Region W49N. Ap. J. Submitted.

Elmegreen, B. G. 1980. Star Formation Behind Shocks. In Giant Molecular Clouds in the Galaxy, eds. P. M. Solomon and M. G. Edmunds (Oxford:Pergamon Press), pp. 255-264.

Elmegreen, B. G., and Elmegreen, D. M. 1978. Star Formation in Shock Compressed Layers. Ap. J. 220:1051-1062.

Elmegreen, B. G. and Lada, C. J. 1977. Sequential Formation of Subgroups in OB Associations. Ap. J. 214:725-741.

Felli, M., Johnston, K. J., and Churchwell, E. 1980. An Unusual Radio Point Source in M17. Ap. J. (Letters) 242:L157-L161.

Fleck, R. C. Jr. 1983. A Note on Compressibility and Energy Cascade in Turbulent Molecular Clouds. Ap. J. (Letters) 272:L45-L48.

Fleck, R. C. Jr. and Clark, F. O. 1981. A Turbulent Origin for the Rotation of Molecular Clouds. Ap. J. 245:898-902.

Freeman, K. C. 1977. Star Formation and the Gas Content of Galaxies. in The Evolution of Galaxies and Stellar Populations. eds. B. M. Tinsley and R. B. Larson (New Haven:Yale Univ. Observatory) pp. 133-156.

Gail, H. P. and Sedlmayer, E. 1979. Dynamical Evolution of Spherical Gas-dust Nebulae, Including Diffusion Effects. Astr. Ap. 76:158-167.

Gilden, D. L. 1984. Clump Collisions in Molecular Clouds: Gravitational Instability and Coalescence. Ap. J. 279:335-349.

Harlow, F. H. and Amsden, A. A. 1975. Numerical Calculation of Multiphase Fluid Flow. J. Comp. Phys. 17:19-52.

Harvey, P. M. and Gatley, I. 1983. Infrared Observations of OB Star Formation in NGC 6334. Ap. J. 269:613-624.

Haschick, A. D. and Ho, P. T. 1983. Formation of OB Clusters: W33 Complex. Ap. J. 267:638-646.

Herbig, G. 1962. Emission-Line Stars Associated with the Nebulous Cluster NGC 2264. Ap. J. 119:483-495.

Herbst, W. and Assousa, G. E. 1977. Observational Evidence for Supernovae-Induced Star Formation: Canis Major R1. Ap. J. 217:473-487.

____________. 1978. The Role of Supernovae in Star Formation and Spiral Structure. In Protostars and Planets, ed. T. Gehrels (Tucson:Univ. Ariz. Press), pp. 368-383.

Ho, P. T. P. and Haschick, A. D. 1981. Formation of OB Clusters: VLA Observations. Ap. J. 248:622-637.

Huang, S. S. and Struve, O. 1954. Stellar Rotation. Ann d'Ap. 17:85-93.

Hughes, V. A. 1982. Formation of a B0.5 Star Due to the Interactions of a Shock Wave with a Molecular Cloud in IC1805. in Regions of Recent Star Formation, eds. R. S. Roger and P. E. Dewdney, (Boston:D. Reidel) pp. 349-355.

Hunter, C. 1962. The Instability of the Collapse of a Self-Gravitating Gas Cloud. Ap. J. 136:594-608.

Hunter, J. H. Jr. 1979. The Influence of Initial Velocity Fields upon Star Formation. Ap. J. 233:946-949.

Hunter, J. H. Jr. and Fleck, R. C. Jr. 1982. Star Formation: The Influence of Velocity Fields and Turbulence. Ap. J. 256:505-513.

Hunter, J. H. Jr., Sandford II, M. T., Whitaker, R. W., and Klein, R. I. 1984. Star Formation in Colliding Gas Flows. in preparation.

Isobe, S. and Sasaki, G. 1982. Globules in the Orion Nebula. III. Age Range of the Stars in the Orion Nebula. Pub. Astron. Soc. Jap. 34:241-247.

Jaffe, D. T. and Fazio, G. G. 1982. Star Formation in the M 17 SW Giant Molecular Cloud. Ap. J. (Letters) 257:L77-L82.

Jaffe, D. T., Hildebrand, R. H., Keene, J., Harper, D. A., Lowenstein, R. F., and Moran, J. M. 1984. Far-IR Selected Star Formation Regions. Ap. J. (Letters) in press.

Jones, T. J., Hyland, A. R., Robinson, G., Smith, R., and Thomas, J. 1980. Infrared Observations of a Bok Globule in the Southern Coalsack. Ap. J. 242:132-140.

Jones, T. J., Hyland, A. R., and Bailey, J. 1984. The Inner Core of a Bok Globule. preprint.

Kahn, F. D. 1969. The Flow of Ionized Gas from a Globule in Interstellar Space. Physica 41:172-189.

Keene, J., Davidson, J. A., Harper, D. A., Hildebrand, R. H., Jaffe, D. T., Lowenstein, R. F., Low, F. J., Pernic, R. 1983. Far-Infrared Detection of Low-Luminosity Star Formation in the Bok Globule B335. Ap. J. (Letters) 274:L43-L47.

Klein, R. I., and Chevalier, R. A. 1978. X-Ray Bursts From Type II Supernovae. Ap. J. 223:L109-L112.

Klein, R. I., Sandford II, M. T., and Whitaker, R. W. 1980 (KSW1). Two-Dimensional Radiation Hydrodynamics Calculations of the Formation of O-B Associations in Dense Molecular Clouds. Space Sci. Rev. 27:275-281.

___________. 1983 (KSW2). Star Formation Within OB Subgroups: Implosion by Multiple Sources. Ap. J. (Letters) 271:L69-L73.

Kossacki, K. 1968. On the Possibility of Pre-Stellar Bodies Formation in Clouds Compressed by Shock Waves. Acta Astr. 18:221-253.

Krügel, E., Stenholm, L. G., Steppe, H., Sherwood, W. A. 1983. The Physical Structure of Globule B335. Astr. Ap. 127:195-200.

Lada, C. J. 1980. Formation of Massive Stars in OB Associations and Giant Molecular Clouds. In Giant Molecular Clouds in the Galaxy, eds. P. M. Solomon and M. G. Edmunds (Oxford:Pergamon Press), pp. 239-253.

Lada, C. J., Blitz, L., and Elmegreen, B. G. 1978. Star Formation in OB Associations. In Protostars and Planets, ed. T. Gehrels (Tucson:Univ. Ariz. Press), pp. 341-367.

LaRosa, T. N. 1983. Radiatively Induced Star Formation. Ap. J. 274:815-821.

Larson, R. B. 1979. Stellar Kinematics and Interstellar Turbulence. M. N. R. A. S. 186:479-490.

___________. 1981. Turbulence and Star Formation in Molecular Clouds. M. N. R. A. S. 194:809-826.

Lathrop, K. D. and Brinkley, F. W. 1973. TWOTRAN-II: An Interfaced, Exportable Version of the TWOTRAN Code for Two-Dimensional Transport. report LA-4848-MS (Los Alamos:Los Alamos National Lab.).

Loren, R. R. 1976. Colliding Clouds and Star Formation in NGC 1333. Ap. J. 209:466-488.

McCutcheon, W. H., Roger, R. S., and Dickman, R. L. 1982. The Molecular Cloud Complex in the Vicinity of IC 5146. Ap. J. 256:139-150.

Mestel, L. and Spitzer, L. Jr. 1956. Star Formation in Magnetic Dust Clouds. M. N. R. A. S. 116:503-514.

Meusinger, H. 1983. On the Past Star Formation Rate in the Solar Neighborhood. Astron. Nachr. 304:285-298.

Miller, G. and Scalo, J. M. 1979. The Initial Mass Function and Stellar Birthrate in the Solar Neighborhood. Ap. J. (Suppl. Ser.) 41:513-547.

Mouschovias, T. Ch. 1981. in Fundamental Problems in the Theory of Stellar Evolution. IAU Symposium 93. eds. D. Sugimoto, D. Q. Lamb, and D. N. Schramm (Boston:D. Reidel), p. 27-62.

Myers, P. C. 1983. Dense Cores in Dark Clouds. III. Subsonic Turbulence. Ap. J. 270:105-118.

Myers, P. C. and Benson, P. J. 1983. Dense Cores in Dark Clouds. II. NH_3 Observations and Star Formation. Ap. J. 266:309-320.

Norman, C. and Silk, J. 1980. Clumpy Molecular Clouds: A Dynamic Model Self-Consistently Regulated by T-Tauri Star Formation. Ap. J. 238:158-174.

Oort, J. H. 1954. Outline of a Theory on the Origin and Acceleration of Interstellar Clouds and O Associations. B.A.N. 12:177-186.

Pumphrey, W. A. and Scalo, J. M. 1983. Simulation Models for the Evolution of Cloud Systems. I. Introduction and Preliminary Simulations. Ap. J. 269:531-559.

Reipurth, B. 1983. Star Formation in Bok Globules and Low-Mass Clouds. I. The Cometary Globules in the Gum Nebula. Astr. Ap. 117:183-198.

Sandford II, M. T. and Whitaker, R. W. 1983. Hydrodynamic Models of Herbig-Haro Objects. M. N. R. A. S. 205:105-121.

Sandford II, M. T., Whitaker, R. W., and Klein, R. I. 1982a (SWK1). Radiation Driven Implosions in Molecular Clouds. Ap. J. 260:183-201.

____________. 1982b (SWK2). Radiation-Hydrodynamics of H II Regions and Molecular Clouds. in Regions of Recent Star Formation, eds. R. S. Roger and P. E. Dewdney, (Boston:D. Reidel) pp. 129-132.

____________. 1984 (SWK3). Radiatively Driven Dust-Bounded Implosions: Formation and Stability of Dense Globules. Ap. J. 282:178-190.

Sargent, A. I. 1979. Molecular Clouds and Star Formation. II. Star Formation in the Cepheus OB3 and Perseus OB2 Molecular Clouds. Ap. J. 233:163-181.

Scalo, J. M. 1978. The Stellar Mass Spectrum. In Protostars and Planets, ed. T. Gehrels (Tucson:Univ. Ariz. Press), pp. 265-287.

Scalo, J. M. and Pumphrey, W. A. 1982. Dissipation of Supersonic Turbulence in Interstellar Clouds. Ap. J. (Letters) 258: L29-L33.

Shu, F. H. 1983. Ambipolar Diffusion in Self-Gravitating Isothermal Layers. Ap. J. 273:202-213.

Shu, F. H. and Tereby, S. 1984. The Formation of Cool Stars From Cloud Cores. In Third Cambridge Meeting on Cool Stars, (Cambridge), in press.

Silk, J. 1984. Molecular Cloud Evolution and Star Formation. in Birth and Infancy of Stars, (Les Houches Summer School Lectures), in press.

Silk, J. and Takahashi, T. 1979. A Statistical Model for the Initial Mass Function. Ap. J. 229:242-256.

Smith, G. H. 1982. The Role of H II Regions During Star Formation and Chemical Enrichment in Globular Clusters. Ap. J. 259:607-616.

Stahler, S. W. 1983. The Birthline for Low-Mass Stars. Ap. J. 274:822-829.

Stahler, S. W., Shu, F. H., and Taam, R. E. 1980a. The Evolution of Protostars. I. Global Formulation and Results. Ap. J. 241:637-654.

____________. 1980b. The Evolution of Protostars. II. The Hydrostatic Core. Ap. J. 242:226-241.

____________. 1981. The Evolution of Protostars. III. The Accretion Envelope. Ap. J. 248:727-737.

Stone, M. J. 1970. Collisions Between H I Clouds. II. Two-Dimensional Model. Ap. J. 159:293-307.

Tajima, T. and Leboeuf, J. N. 1980. Kelvin-Helmholtz Instability in Supersonic and Super-Alfvenic Fluids. Phys. Fluids, 23:884-888.

Tohline, J. E. 1982. Hydrodynamic Collapse. Fund. Cos. Phys. 8:1-82.

____________. 1984. Do We Understand Rotating Isothermal Collapses Yet? Icarus, submitted.

Wesselius, P. R., Beintema, D. A., and Olnon, F. M. 1984. IRAS Observations of Two Early-Type Pre Main Sequence Stars in the Association Cha I. Ap. J. (Letters), 278:L37-L39.

Whitworth, Ant. 1979. The Erosion and Dispersal of Massive Molecular Clouds by Young Stars. M. N. R. A. S. 186:59-68.

Wilking, B. A. and Lada, C. J. 1983. The Discovery of New Embedded Sources in the Centrally Condensed Core of the Rho Ophiuchi Dark Cloud: The Formation of a Bound Cluster? Ap. J. 274:698-716.

Woodward, P. R. 1976. Shock-Driven Implosion of Interstellar Gas Clouds and Star Formation. Ap. J. 207:484-501.

Figure Captions

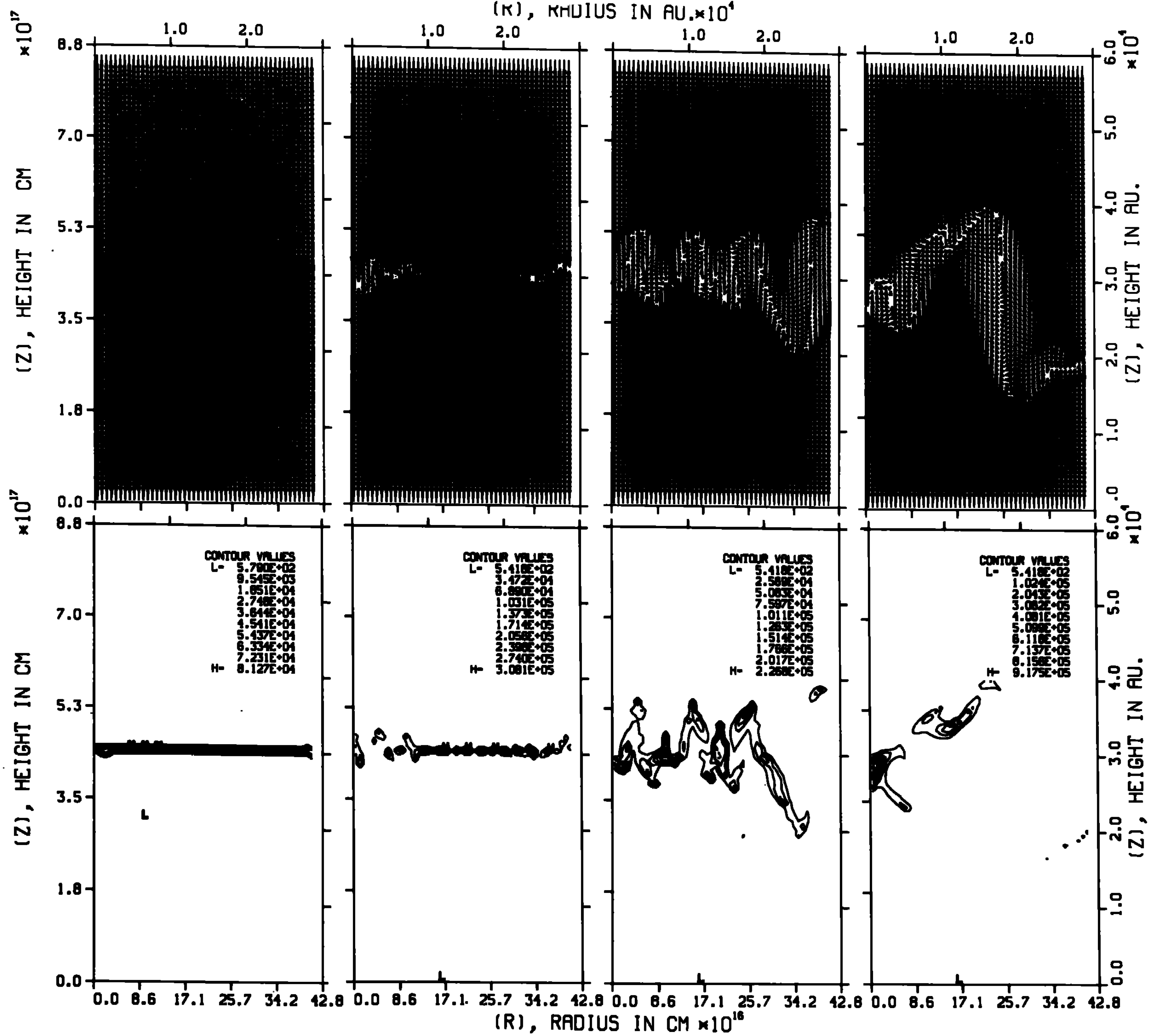
Fig. 1 Time evolution of colliding gas flows at $t = 1.24 \times 10^{12}$, 2.90×10^{12}, 6.44×10^{12}, and 1.06×10^{13} s. A continuous flow of clumpy gas at $n_H \cong 500$ cm^{-3} ($\mp$ 10 %) enters the top and bottom of the computing grid at 5.0 km s^{-1}. The collision of the flows results in the formation of an unstable, self-gravitating disk at $t \cong 1.24 \times 10^{12}$ s (left). The disk fragments (center panels) and forms a centrally condensed, Jeans instable object (right) at $t \cong 1.06 \times 10^{13}$ s. Contour values are cm^{-3} units, the high (H) and low (L) levels are marked, and the fifth contour level is dashed.

Fig. 2 Contours of neutral (left) and ionized (right) hydrogen and the gas velocity field for a low-mass globule compressed by radiation from an O9 star located 8 pc below the computing grid (the Cloud 10 model, SWK1). The maximum velocity is $\cong$ 15 km s^{-1}. The inner (H) and outer contours of neutral hydrogen density are 3.16×10^4 and 3.51×10^3 cm^{-3}, and the contour spacing is 3.5×10^3 cm^{-3}. The closed (H) contour on the axis in the ionized hydrogen plot is 179 cm^{-3}, the lowest contour is 20 cm^{-3}, and the contour spacing is 20 cm^{-3}.

Fig. 3 Gas density (right) and absolute temperature (left) contours for the radiation implosion driven by multiple sources. Contour values are in cm^{-3} and K units, the fifth contour level is dashed, and the high (H) and low (L) levels are marked. From KSW2 (1983).

Fig. 4 Schematic geometry for the formation of an OB subgroup by radiation driven implosions. From KSW2 (1983). Primary generation O and B stars (asterisks) implode cloud clumps which subsequently form new OB stars (dashed circles). These implode the remaining clumps, as indicated by the wavy lines of interaction.

Fig. 5 Schematic diagram of a radiatively driven dust-bounded implosion, from SWK3 (1984). In (a), an O9 star illuminates a dusty molecular cloud. In (b), an I-S front propagates a shock into the neutral gas and dust (diagonal lines) and compresses gas behind the shock (scattered lines). Ionized gas (shading) ablates from the neutral cloud edge at the I-front (dashed line). In (c), the shock converges toward the symmetry axis and dust accumulates in the I-front (dark shading). In (d), a globule of neutral gas and dust is formed and it is surrounded by a dust-bounded I-front (dark shading) within an H II region (light shading).



(R), RADIUS IN AU.×10^4
1.0
2.0
(Z), HEIGHT IN CM ×10^17
8.8
7.0
5.3
3.5
1.8
0.0
(Z), HEIGHT IN AU. ×10^4
6.0
5.0
4.0
3.0
2.0
1.0
.0
CONTOUR VALUES
L= 5.790E+02
9.545E+03
1.851E+04
2.748E+04
3.644E+04
4.541E+04
5.437E+04
6.334E+04
7.231E+04
H= 8.127E+04
CONTOUR VALUES
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3.472E+04
6.890E+04
1.031E+05
1.373E+05
1.714E+05
2.058E+05
2.398E+05
2.740E+05
H= 3.081E+05
CONTOUR VALUES
L= 5.418E+02
2.588E+04
5.083E+04
7.597E+04
1.011E+05
1.263E+05
1.514E+05
1.766E+05
2.017E+05
H= 2.268E+05
CONTOUR VALUES
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1.024E+05
2.043E+05
3.082E+05
4.081E+05
5.098E+05
6.118E+05
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H= 9.175E+05
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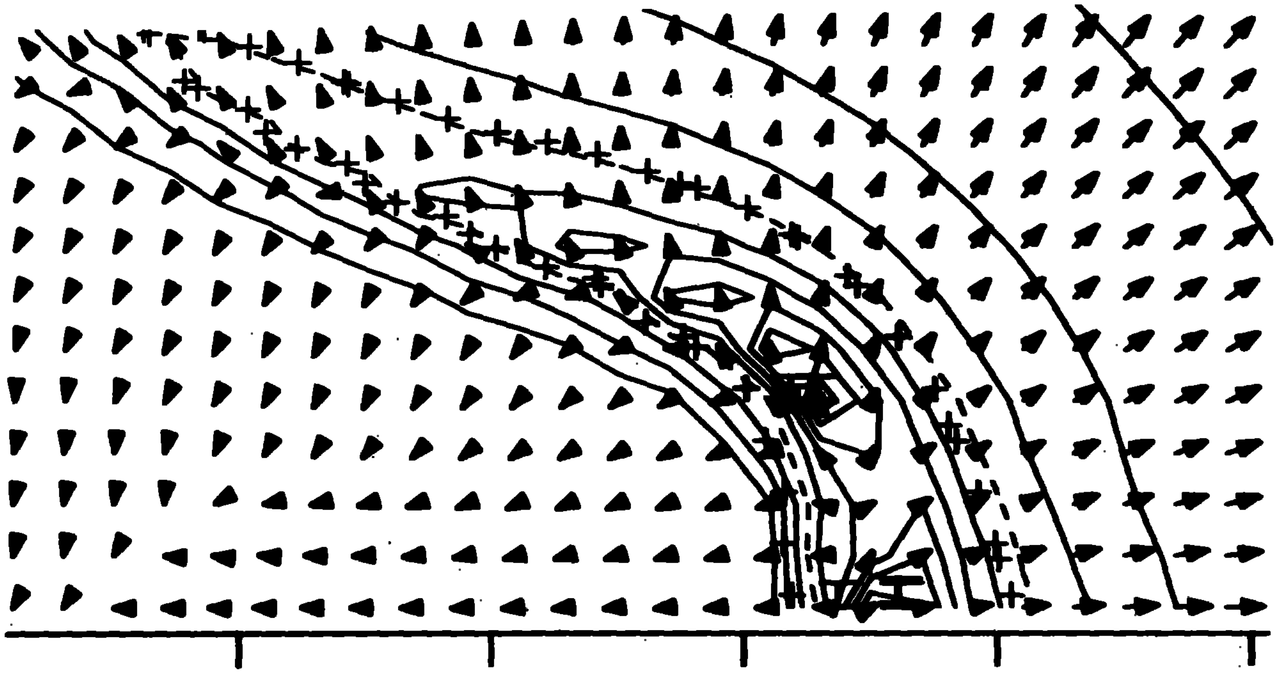
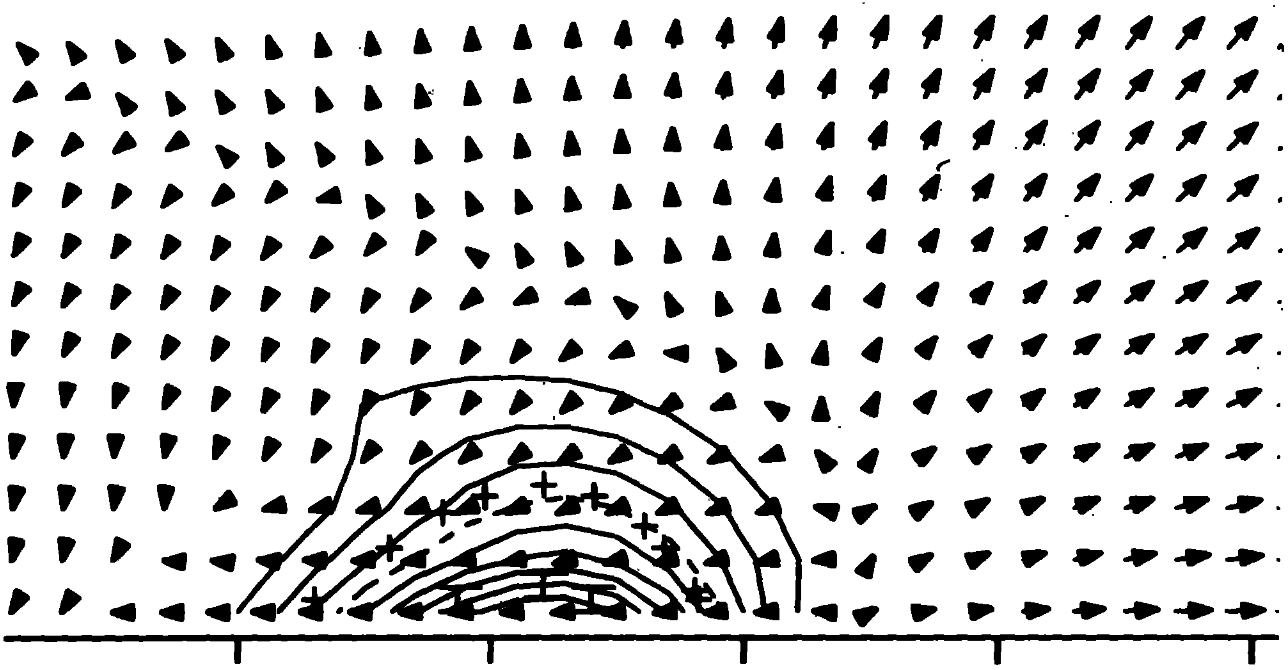
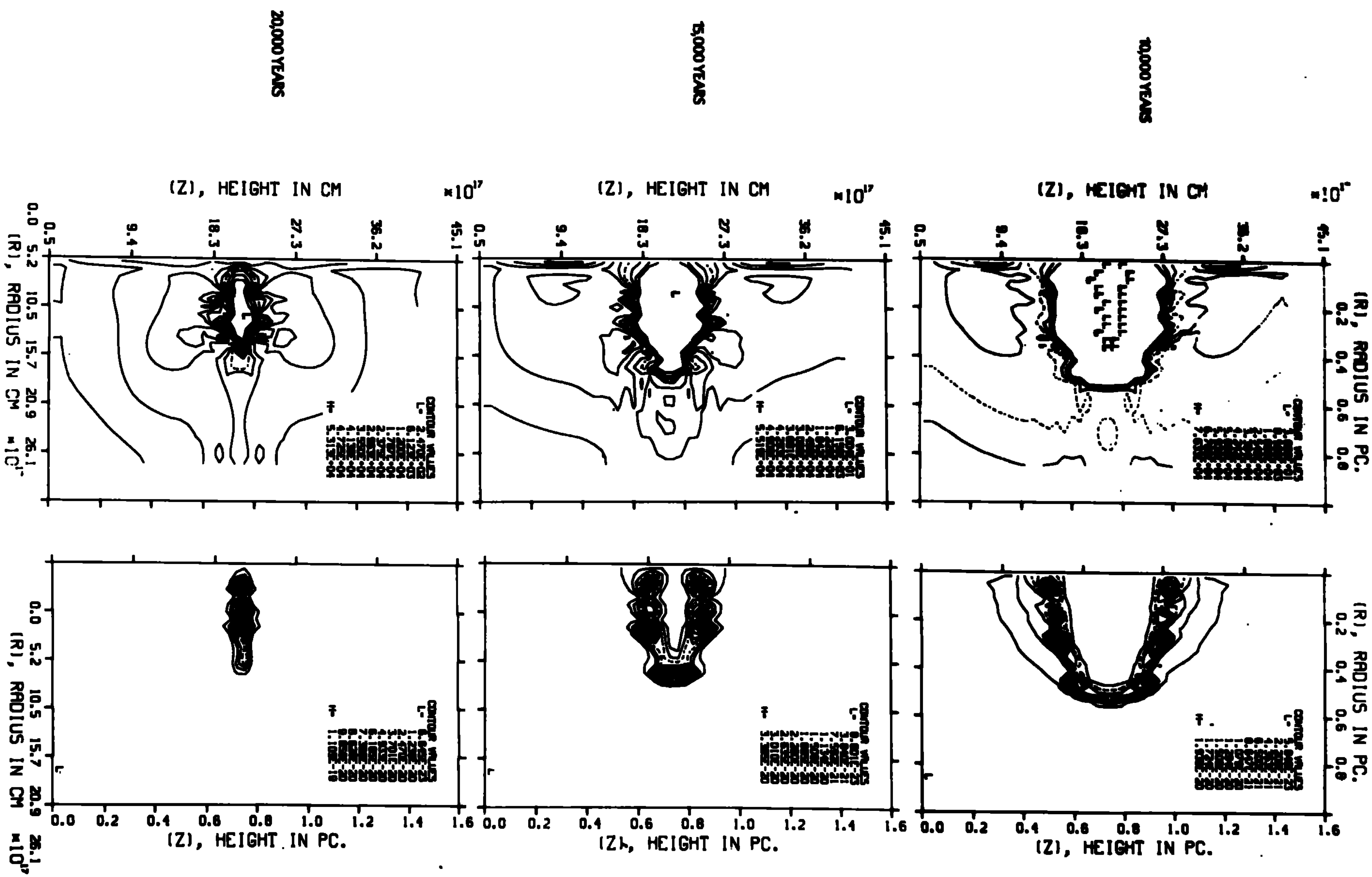
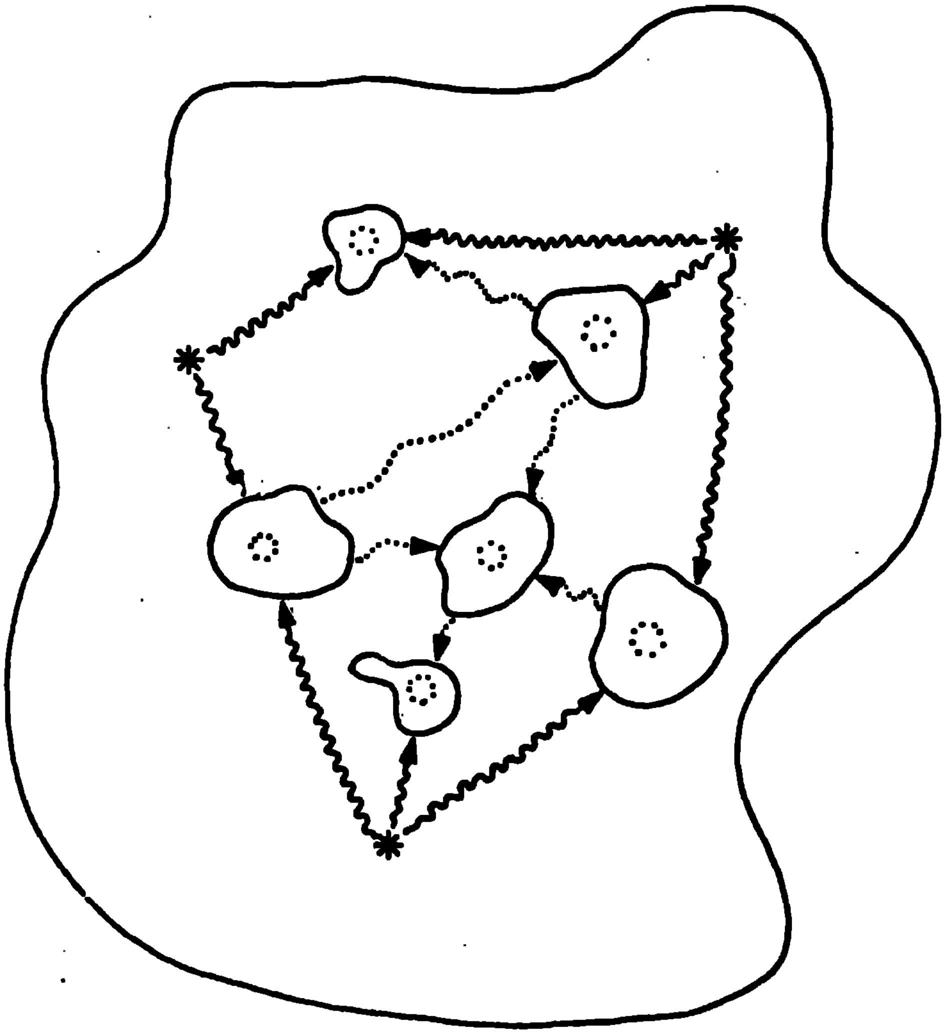
(R), RADIUS IN CM ×10^16



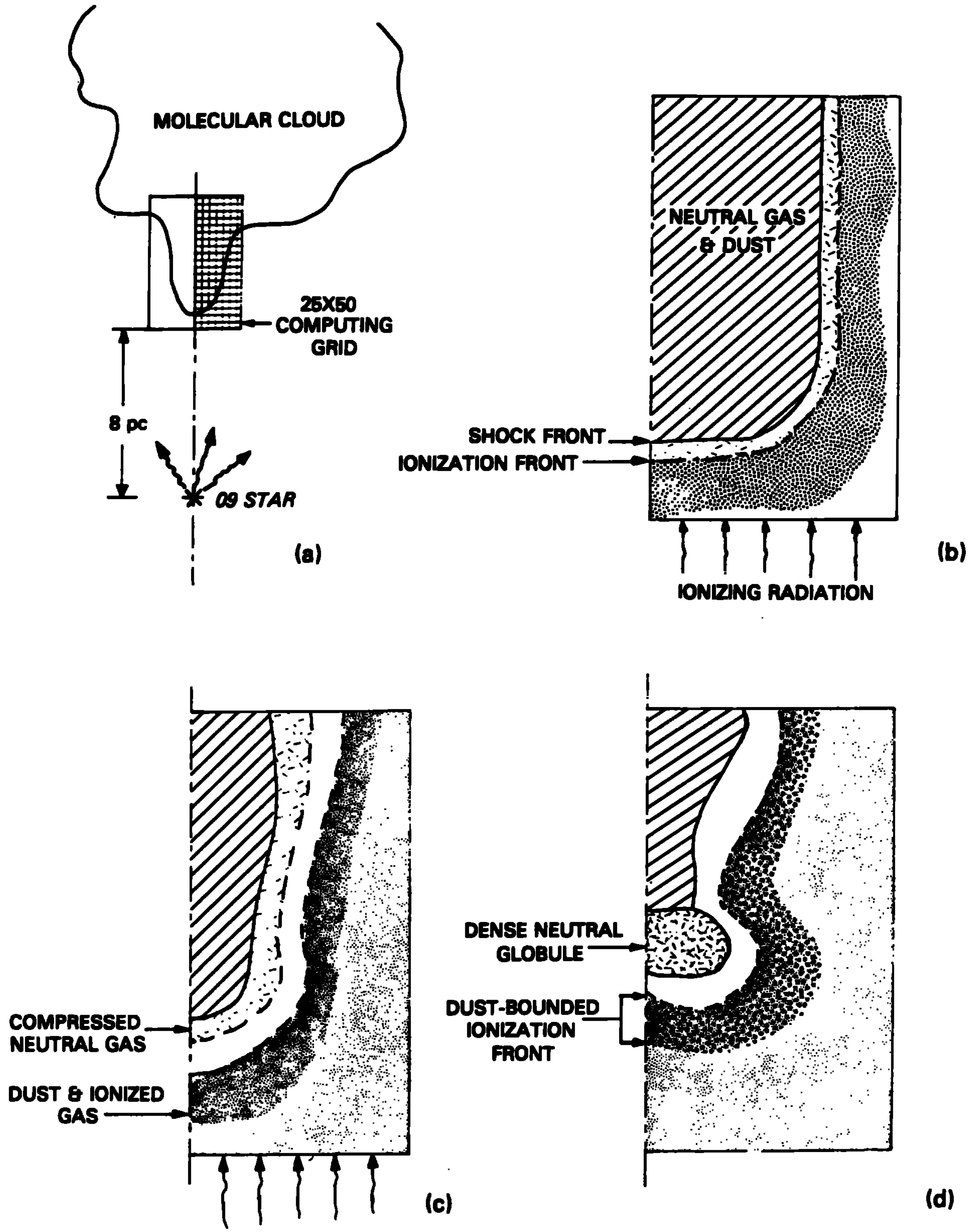




20,000 YEARS
15,000 YEARS
10,000 YEARS
(Z), HEIGHT IN CM
(R), RADIUS IN CM
(R), RADIUS IN PC.
(Z), HEIGHT IN PC.
CONTOUR VALUES



(4)


MOLECULAR CLOUD
25X50
COMPUTING
GRID
8 pc
09 STAR
(a)
NEUTRAL GAS
& DUST
SHOCK FRONT
IONIZATION FRONT
IONIZING RADIATION
(b)
COMPRESSED
NEUTRAL GAS
DUST & IONIZED
GAS
(c)
DENSE NEUTRAL
GLOBULE
DUST-BOUNDED
IONIZATION
FRONT
(d)